

A Scintillating Fiber Detector for Real-Time Beam Monitoring in Particle Therapy

L. Testa^{1, 2, 3}, **G. Battistoni**⁴, **A. Burattini**⁵, **M. Carruezzo**^{6, 3},
G. Franciosini^{6, 3}, **M. Garbini**², **L. Frassi**¹, **M. Magi**⁶,
M. Marafini^{2, 3}, **I. Mattei**⁴, **E. Minucci**^{2, 7}, **S. Muraro**⁴,
F. Quattrini^{1, 3, 5}, **A. Sarti**^{6, 3}, **A. Schiavi**^{6, 3}, **M. Toppi**^{6, 3},
G. Traini³, **A. Vannucci**^{2, 5}, **V. Patera**^{6, 3}

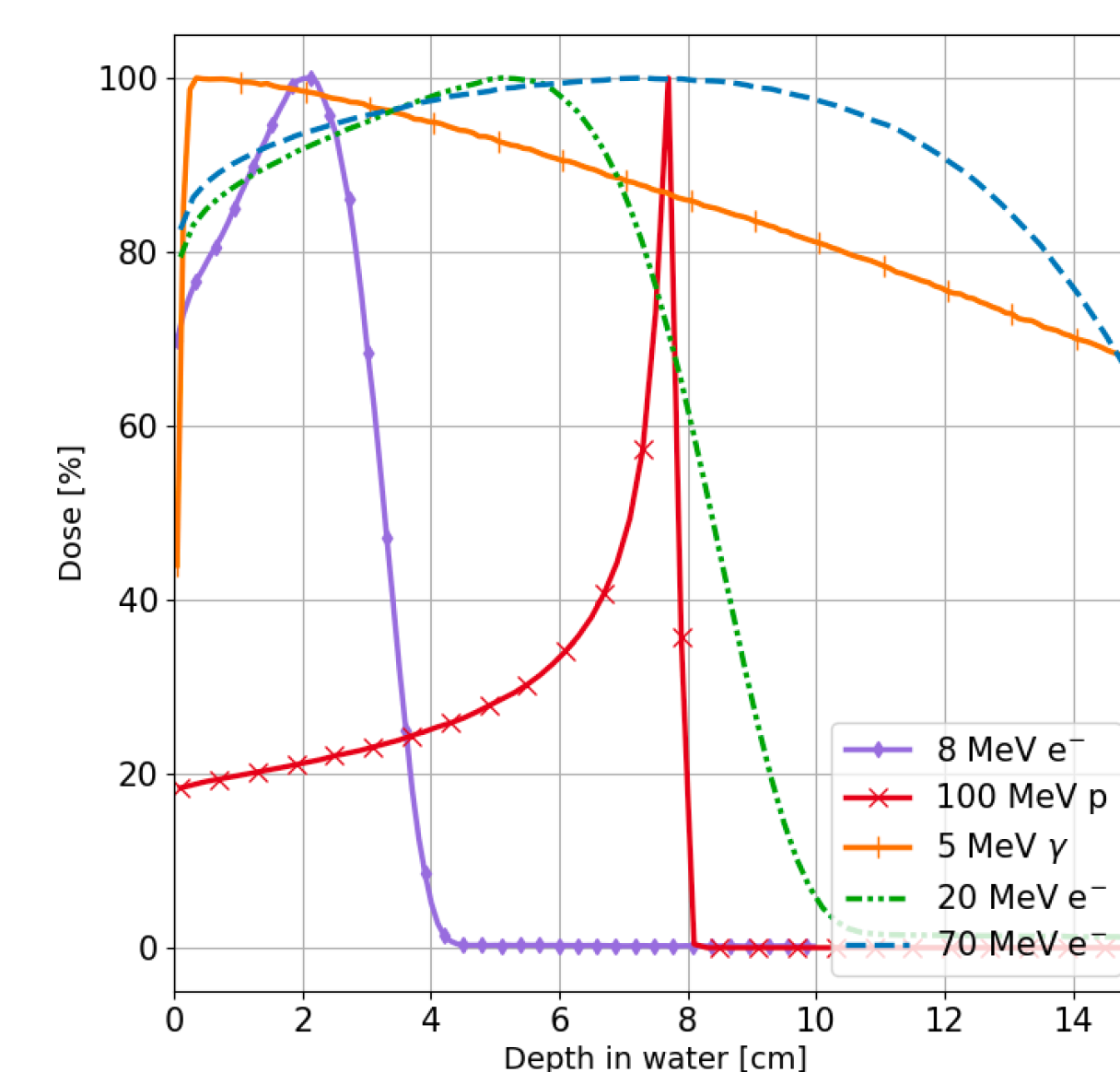
¹ Department of Physics, Sapienza University of Rome, Rome, Italy,
² CREF Centro Ricerche Enrico Fermi, Rome, Italy,
³ INFN Rome 1 Section, Rome, Italy,
⁴ INFN Milan Section, Milan, Italy,
⁵ Postgraduate School of Medical Physics, Sapienza University of Rome, Rome, Italy,
⁶ SBAI Department of Basic and Applied Sciences for Engineering, Sapienza University of Rome, Italy,
⁷ LNF INFN Frascati National Laboratories, Frascati, Italy



Particle therapy

Particle Therapy (PT) represents an advanced form of oncological radiotherapy, utilizing beams of protons and carbon ions to deliver highly conformal dose distributions [1].

By exploiting the energy deposition profile of the Bragg Peak PT maximizes tumor control while significantly sparing surrounding healthy tissues. Also, the high radiobiological effectiveness of ions offers a superior advantage in treating radio-resistant tumors compared to conventional X-rays.



The challenges

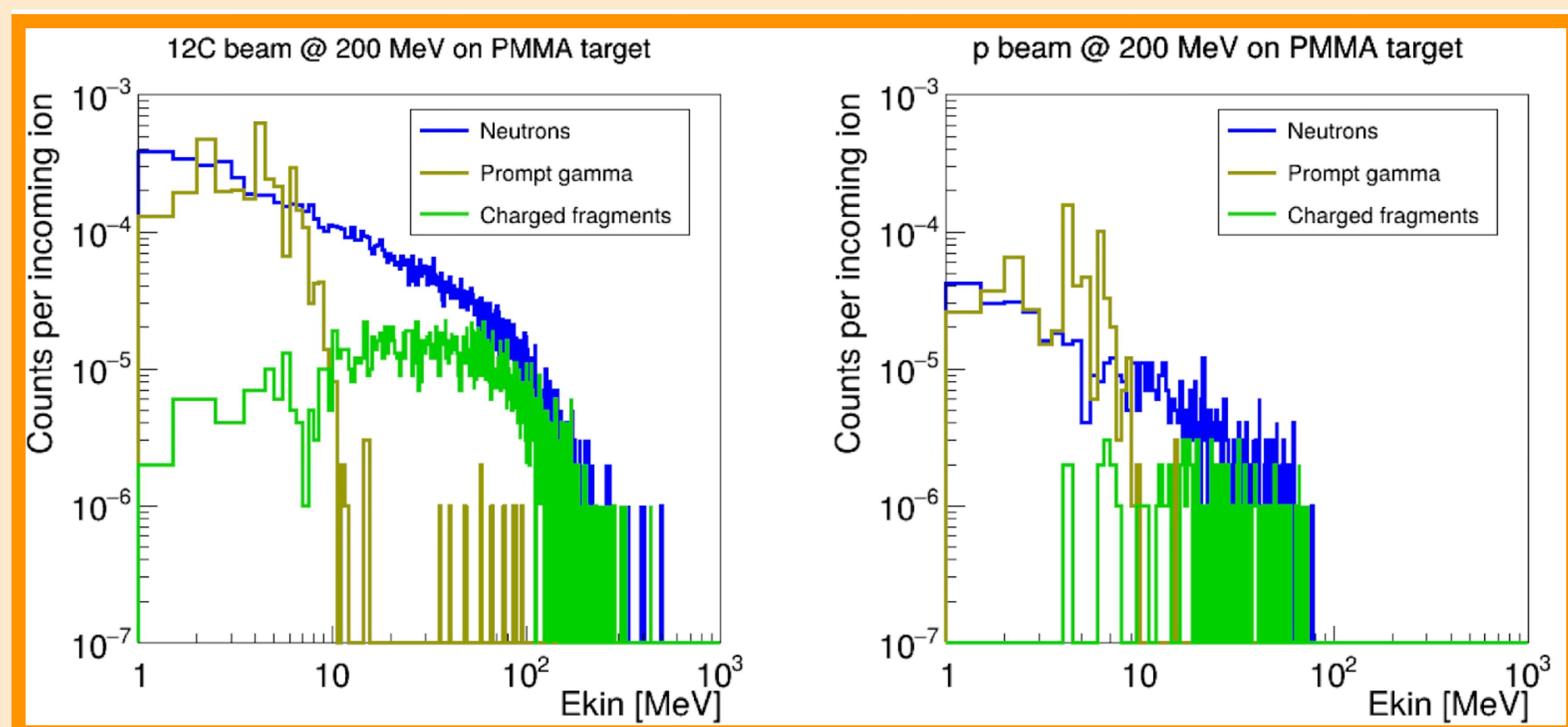
Current PT precision is hindered by significant uncertainties:

- Anatomical variations (weight loss, cavity filling, ..) cause unpredictable dose shifts.
- Patient motion turns the tumor into a moving target.

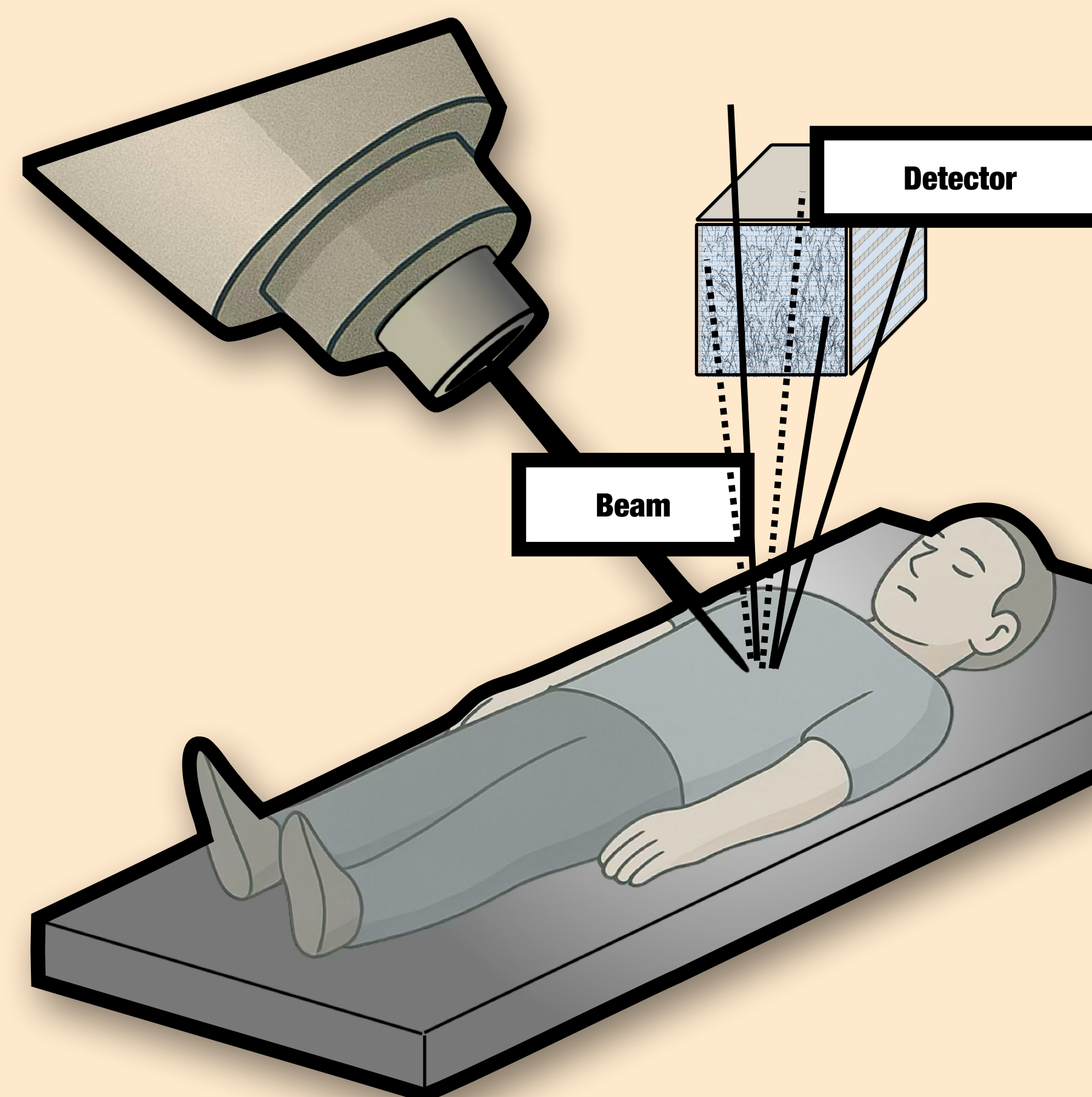
To date, there is no robust system capable of real-time, in vivo monitoring to bridge this gap and ensure truly adaptive, motion-resilient treatments.

The strategy

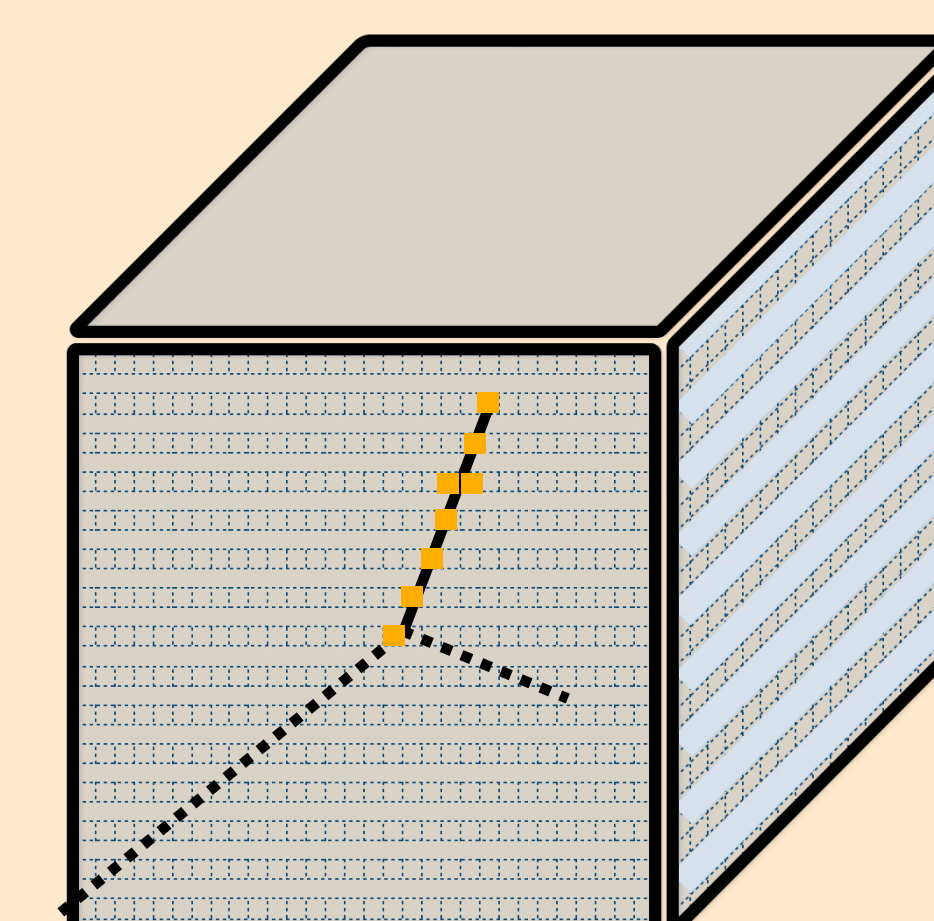
To overcome these limitations, we propose a technology that exploits the full flux of secondary radiation—photons, neutrons, and charged fragments—generated by the interaction of the therapeutic beam with the patient's tissues.



Secondary particles emerging from a PMMA target ($5 \times 5 \times 20 \text{ cm}^3$) irradiated by carbon ion and proton beams. For charged fragments, kinetic energy is expressed in MeV/u.

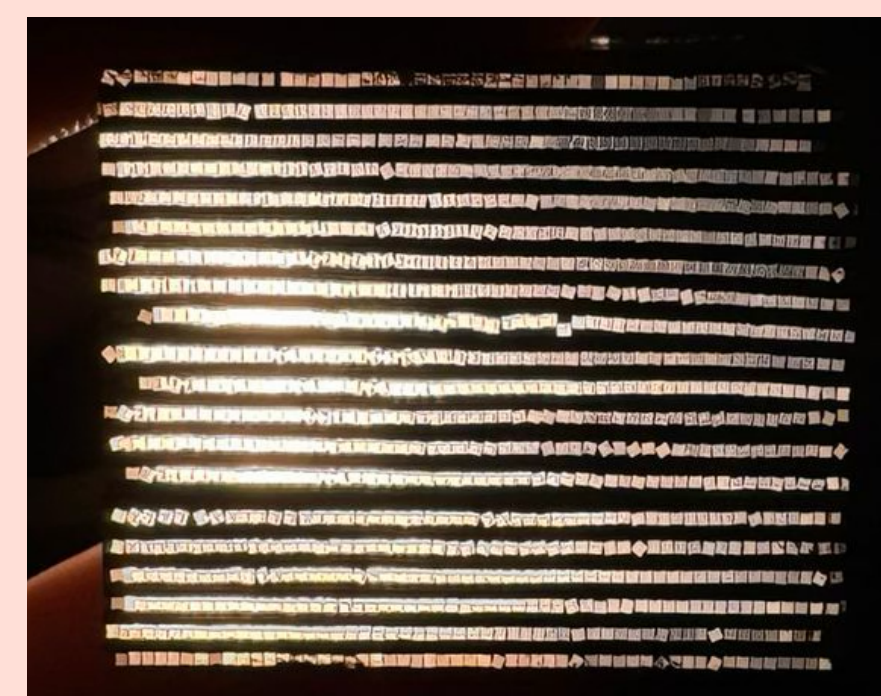


A compact matrix obtained by the superposition of plastic scintillator fiber layers X-Y oriented. The track of charged particles is detected allowing for secondary particle direction reconstruction [2].



The detector

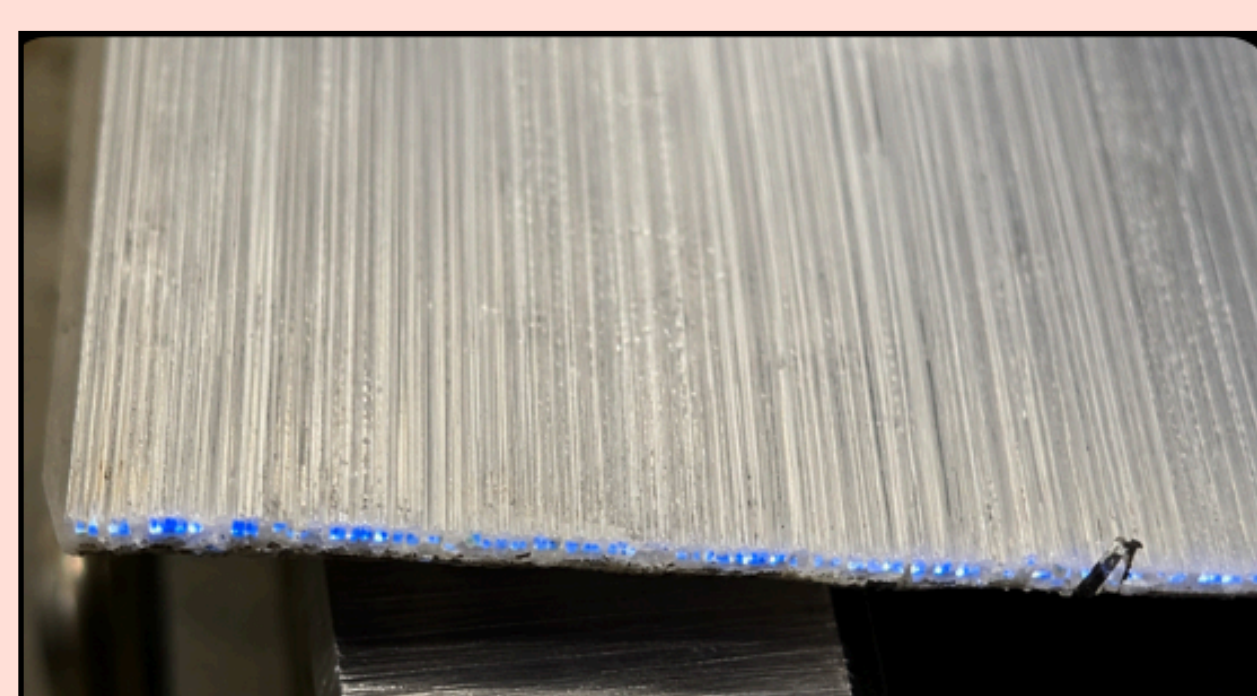
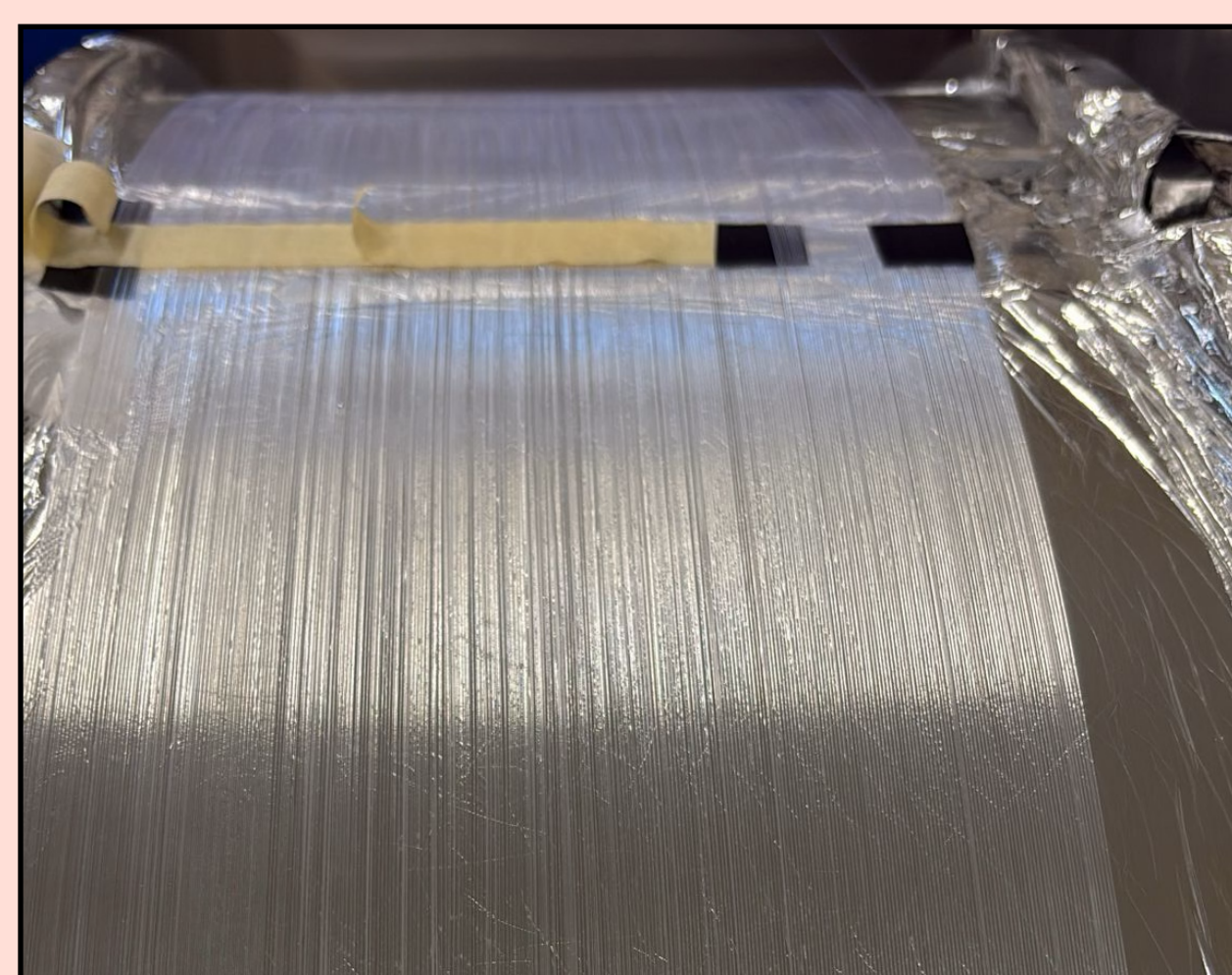
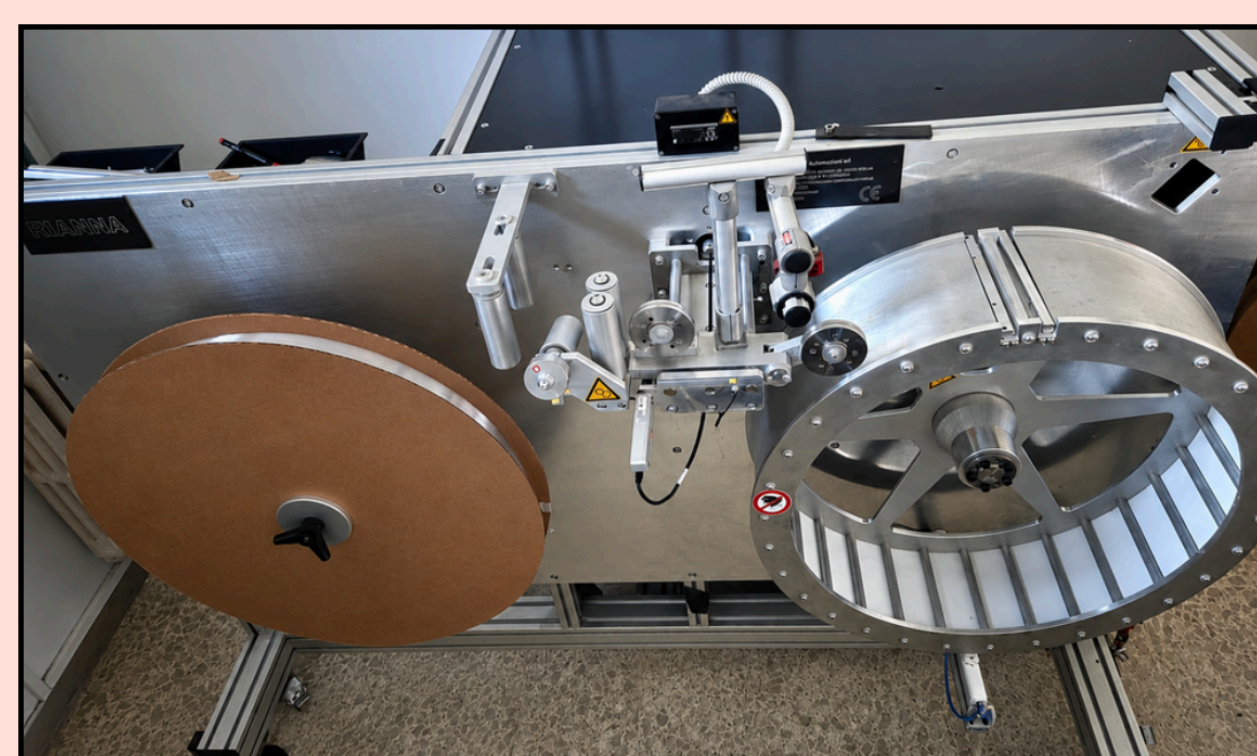
For the tracking of secondary radiation, we developed a dedicated fiber-based detector. A dedicated machine is utilized to precisely align the fibers and assemble individual planes of thin plastic scintillating fibers.



Several prototypes have been realised with fibres: squared single and double cladding $250\mu\text{m}$, $500\mu\text{m}$, $700\mu\text{m}$ and rounded sigle cladding 1mm.

The assembled fiber core is directly coupled to a custom SPAD-based readout sensor named SBAM2-Chip.

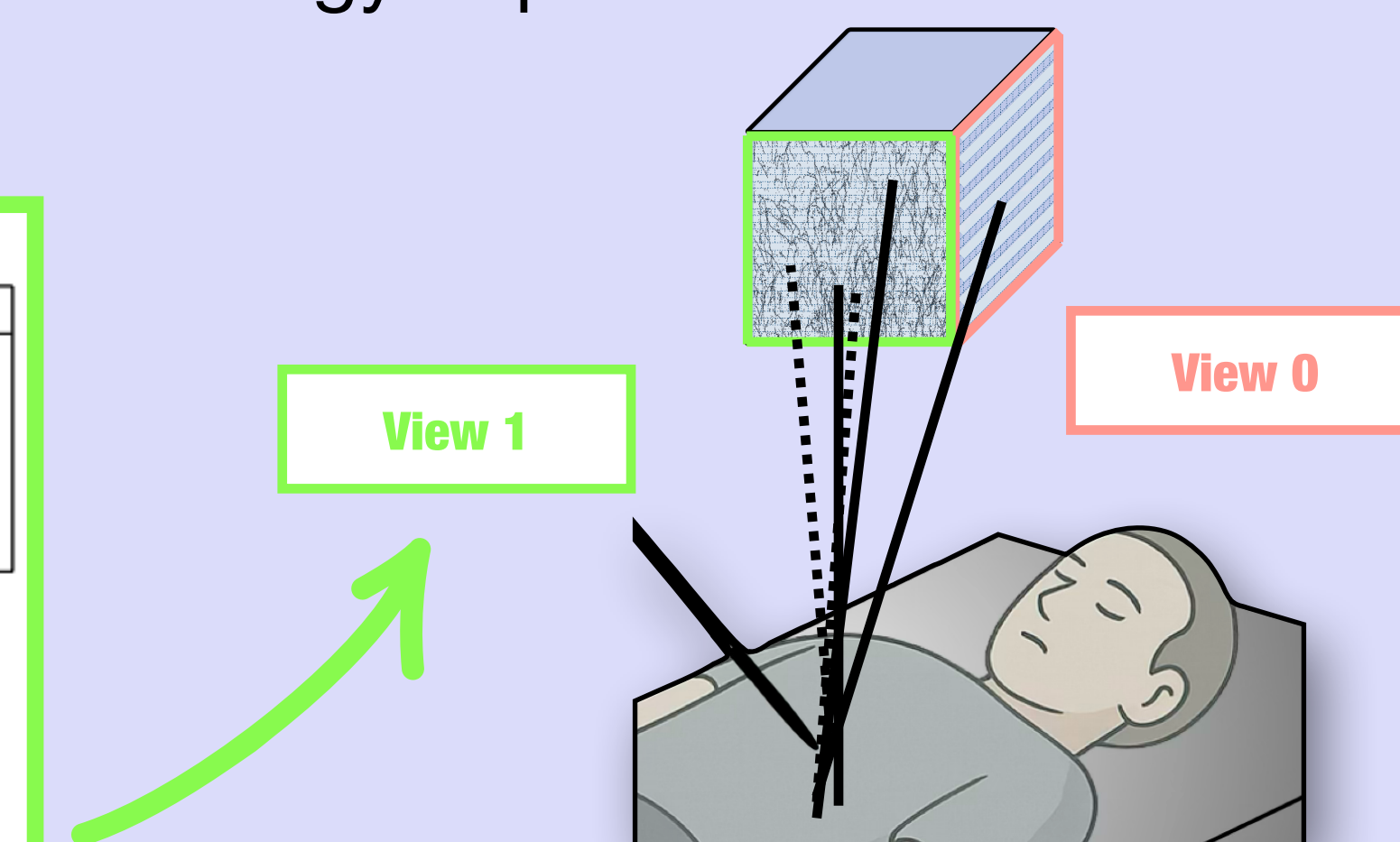
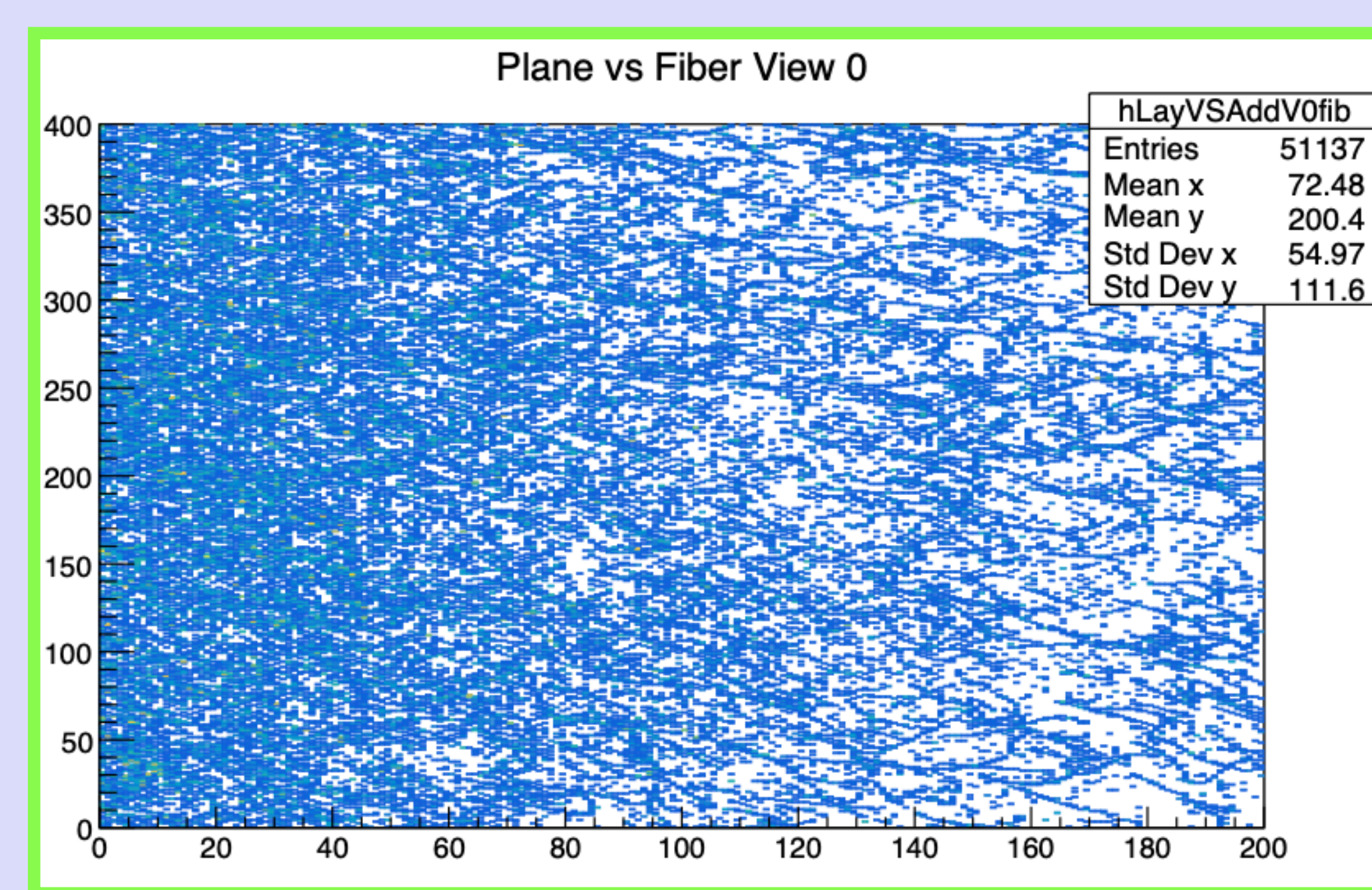
The sensor features a 48×32 pixels ($250 \times 250 \mu\text{m}^2$), enabling high-granularity detection over an $12 \times 8 \text{ mm}^2$ active area.



The workflow

Rather than reconstructing individual secondary-particle events the system integrates all scintillation light associated with a single pencil beam over its entire duration.

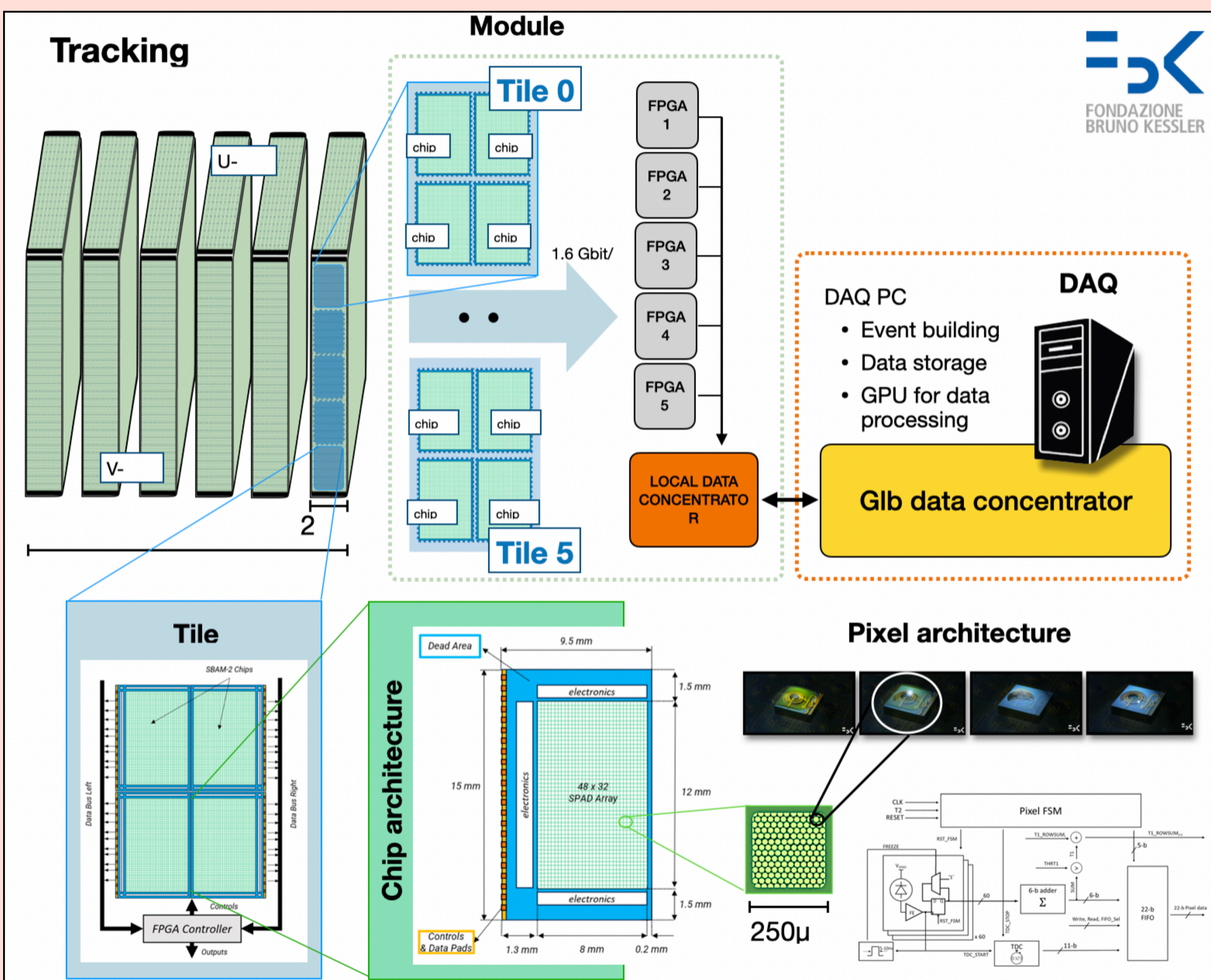
The ultra-sensitive SBAM2 chip and a dedicated FPGA-based DAQ capture these cumulative photons in real time to generate integrated 2D images of energy deposition.



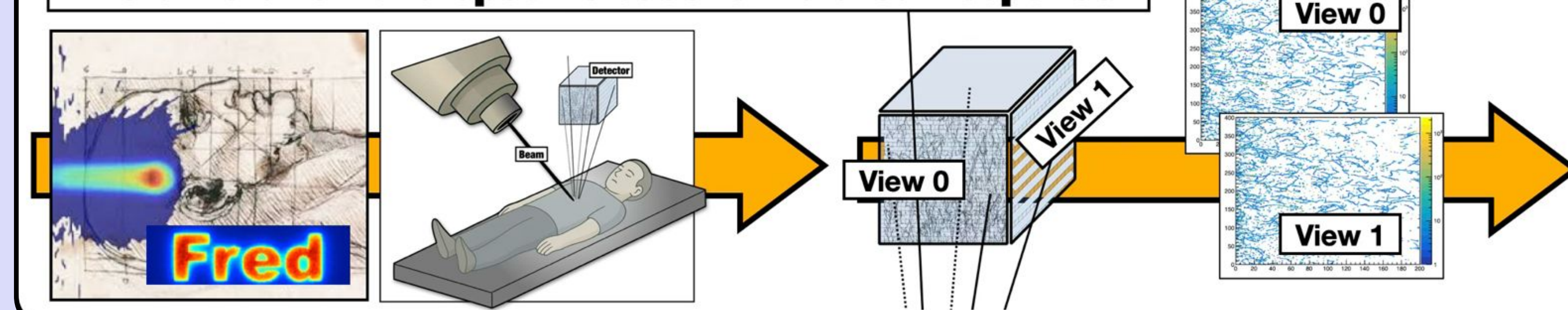
Expected secondary particles tracks visualisation in the FLUKA MC simulation of the detector (two views). The simulation in the picture has been obtained with 10^7 protons (100 MeV) - one pencil beam.

To train the system, FLUKA [3] and FRED [4] Monte Carlo codes simulate both the nominal treatment plan and various clinical deviations (such as patient motion and anatomical changes). For each specific scenario, multiple simulations are performed using different randomized seeds to ensure statistical robustness, yielding the corresponding expected detector images.

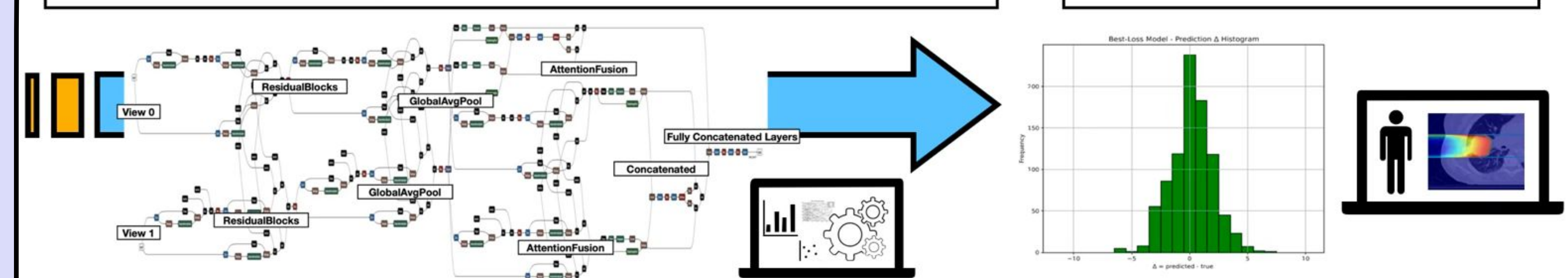
Finally, a patient-specific Convolutional Neural Network (CNN) is trained on these images to distinguish between conforming and non-conforming deliveries, enabling real-time verification and anomaly detection during beam delivery.



MC simulation of a specific case: Simulated Response



AI-Elaboration



AI-Feedback

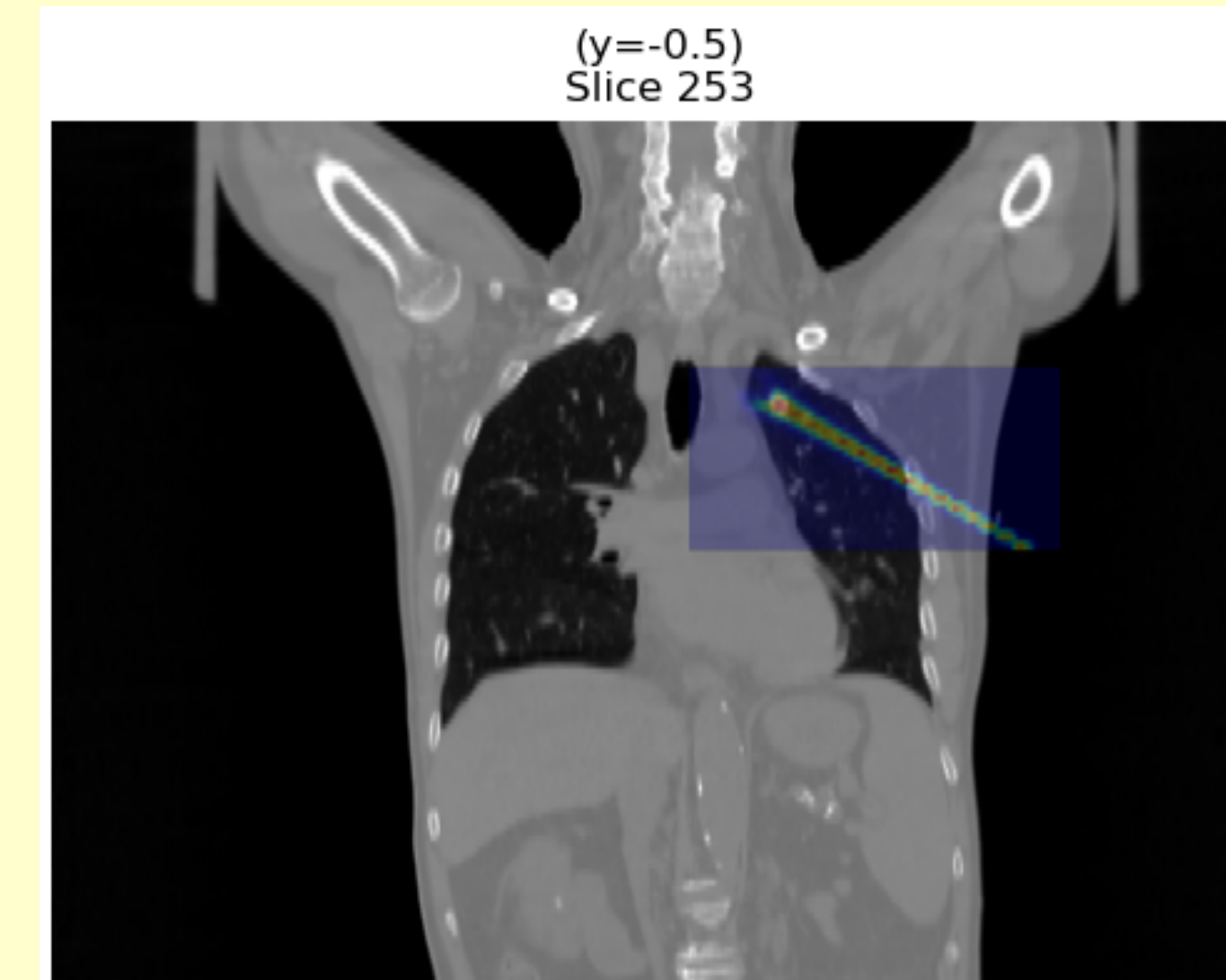
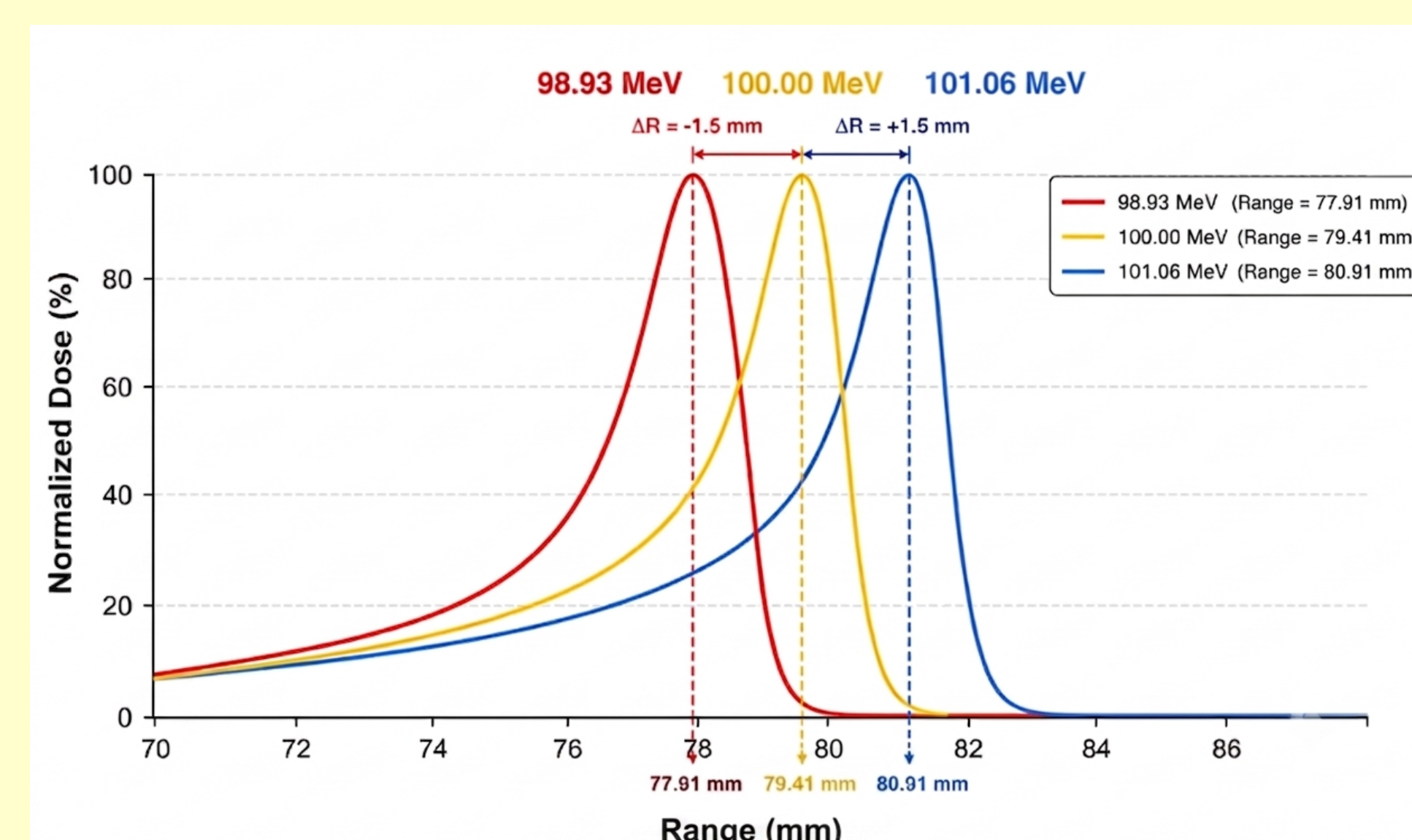
Schematisation of the development process and validation of AI methods

First Results

A study was conducted to evaluate the network's ability to reconstruct beam range variations using a lung cancer patient case. Range variations were obtained by directly modulating the incident beam energies around a 100 MeV baseline, shifting the Bragg peak across the patient's CT planes to construct the training dataset.

The core architecture consists of a Siamese Network with a ResNet-18 backbone. The results are highly accurate, achieving **mm precision**—with a minimum Mean Absolute Error of 0.78 mm.

Crucially, the inference time is of **12 ms** per image pair, demonstrating that this pipeline is perfectly suited for real-time applications in a clinical environment.



References

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